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An experimental investigation of the combustion performance of human faeces

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HIGHLIGHTS

- Dry human faeces have a Higher Heating Value (HHV) of 24 MJ/kg.
- Faeces combustion was investigated using a bench-scale downdraft combustor test rig.
- Combustion temperature of 431–558 °C was achieved at air flow rate of 10–18 L/min.
- Fuel burn rate of 1.5–2.3 g/min was achieved at air flow rate of 10–18 L/min.
- Combustion temperature of up to 600 ± 10 °C can handle 60 wt.% moisture in faeces.

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ABSTRACT

Poor sanitation is one of the major hindrances to the global sustainable development goals. The Reinvent the Toilet Challenge of the Bill and Melinda Gates Foundation is set to develop affordable, next-generation sanitary systems that can ensure safe treatment and wide accessibility without compromise on sustainable use of natural resources and the environment. Energy recovery from human excreta is likely to be a cornerstone of future sustainable sanitary systems. Faeces combustion was investigated using a bench-scale downdraft combustor test rig, alongside with wood biomass and simulant faeces. Parameters such as air flow rate, fuel pellet size, bed height, and fuel ignition mode were varied to establish the combustion operating range of the test rig and the optimum conditions for converting the faecal biomass to energy. The experimental results show that the dry human faeces had a higher energy content (~25 MJ/kg) than wood biomass. At equivalence ratio between 0.86 and 1.12, the combustion temperature and fuel burn rate ranged from 431 to 558 °C and 1.53 to 2.30 g/min respectively. Preliminary results for the simulant faeces show that a minimum combustion bed temperature of 600 ± 10 °C can handle faeces up to 60 wt.% moisture at optimum air-to-fuel ratio. Further investigation is required to establish the appropriate trade-off limits for drying and energy recovery, considering different stool types, moisture content and drying characteristics. This is important for the design and further development of a self-sustained energy conversion and recovery systems for the NMT and similar sanitary solutions.

1. Introduction

Human faeces is a rich source of biomass having a mixture of undigested fats, protein, water, polysaccharide, bacterial biomass, gut secretions, cell shedding and ash [1]. This useful resource is typically treated as a waste material, and openly disposed in the environment by the nearly 1 billion people world-wide who have no access or do not use a toilet. It is estimated that 40% of the world's population (about 2.4 billion people) lack adequate sanitation facilities, particularly in developing countries [2]. In these areas, >90% of the faeces generated are disposed into the open without treatment, polluting surrounding lakes and rivers [3]. Even in communities with modern sanitary systems, wastewater often leak into the environment, due to improper usage and maintenance of septic systems, putting the groundwater at risk of contamination, especially areas with high water table. These scenarios pose a number of health and environmental hazards including the outbreak of infectious diseases and parasitic worms. The world's population is projected to reach close to 10 billion by 2050 [4]; consequently, poor sanitation is projected to increase due

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to rapid urbanization and overburdening of already stressed waste treatment systems. Therefore, the development and universal access of improved sanitation facilities have become a global priority.

The Reinvent the Toilet Challenge (RTTC) of the Bill and Melinda Gates Foundation is set to develop affordable, next-generation sanitary systems that can work without connection to external water, energy or sewerage systems [5]. The Nano-Membrane toilet (NMT) is an example of such a unique off-grid, household-scale toilet solution that is being developed at Cranfield University to safely treat human waste onsite [6]. This unit will integrate a compact energy conversion system that can thermally-treat human faeces, without external energy and water supply. The energy recovered can then be used to meet the toilet's energy requirement to ensure the self-sustained operation of the NMT unit.

Among thermochemical conversion processes, combustion is a promising and the most mature technology targeted for treating biomass, [7]. It is an exothermic reaction that ensures the complete conversion of a fuel in the presence of an oxidant and heat, with the product gas largely constituted by carbon dioxide (CO_2). Combustion can consist of rapid oxidation of the fuel, which is characterised by high temperatures of >1000 °C with the visible presence of flames, or a slow, progressive, flameless, and relatively low temperature reaction, referred to as smouldering. The latter involves the oxidation of the fuel in the gas phase surrounding the fuel [8] with progressive burn, spread and heat release rate. Peak temperatures for smouldering are reported in the range of 500–700 °C [8], which could be low as 250 °C [9]. It involves the thermal degradation of the fuel, evolution of volatiles, and resulting visible glow of heat that propagates into flames, depending on oxygen availability, the presence of stable source of heat (external or previously heated material) as well as feedstock composition and characteristics [10,11].

Smouldering has recently gained importance in practice as an applicable technology. Some of its recent applications include remediation of coal tar [12]; combustion of wood biomass [10,11,13]; treatment of bio-solids from wastewater treatment plant [14]; remediation of oil contaminated soil [15] and faeces treatment [16,17]. Yermán et al. [16] showed that a self-sustained smouldering combustion can be applied to treat moist faeces under given sand pack height, sand-to-faeces ratio, air-to-fuel ratio, and faecal moisture limit. Their studies examined the smouldering combustion of surrogate faeces and validated the process for faeces treatment using dog faeces. Wall et al. [17] investigated the influence of moisture content on smouldering velocity and upscaling of the process. Both studies showed that smouldering can be applied for faeces treatment in on-site sanitation systems, although, this was not demonstrated with human faeces. The operational parameters such as sand pack height and sand-to-faeces mass ratio require sand as a porous medium in the combustor, which are not typical characteristics of a conventional combustor. Thus, little is known about the fundamental combustion processes of human faeces.

Other experimental studies have explored processes such as pyrolysis [18] and hydrothermal carbonization [19] to treat human faeces; although, the development of these technologies is in the early stages and could have added complexities and costs. Ward et al. [18] examined the HHV of real and synthetic faecal char at pyrolysis temperature of 300–750 °C and showed that the faecal char obtained at pyrolysis temperature of 300 °C had a comparable HHV with wood char. Afolabi et al. [19] employed microwave-assisted hydrothermal carbonization to treat human faeces at temperatures of 160–200 °C and residence time of 30–120 min under autogenous pressure, and recovered char and ammonia. These studies confirm that human faeces have unique resource recovery potentials. Monhol and Martins [20] investigated the co-combustion of polyethylene waste and charcoal in a combustion cell and compared the outcomes with the combustion of human faeces. Their study showed that the temperature profile from human faeces combustion was more uniform than co-combustion of polyethylene and charcoal. Earlier studies by the same authors [21] focussed on the ignition properties of these fuels; however, little is shown on the operating conditions for handling the combustion of human faeces.

Unlike well-established fuels with uniform fuel characteristics such as coal, the physical and chemical characteristics of human faeces vary with nutritional intake, health status, gender, body weight and age of individuals [1]. Faeces also possess complex compositional characteristics, such as the presence of a viscous "sticky" substance, possibly from the linings of the intestinal wall, which makes handling and pre-treating of the samples difficult. There is therefore the need to understand the combustion processes of human faeces and establish the right operating range for fuel conversion, considering sample variabilities and uncertainties. This study describes the combustion performance of a bench-scale downdraft combustor test rig when utilised for human faeces combustion. Initial set of analyses were conducted using simulant faeces and wood biomass to ensure repeatability, for fuel comparison and to understand the combustion operating conditions of the test rig. Parameters such as fuel moisture content, air flow rate, fuel pellet size and ignition mode were investigated. Performance evaluation was carried out on the basis of combustion temperature, fuel burn rate, modified combustion efficiency (MCE) and carbon conversion efficiency (η_{CCE}).

2. Methods

2.1. Fuel characterization

About 3 kg of fresh human faeces was collected and stored in a freezer at −85 °C, over a period of two weeks to preserve and prevent microbial degradation of the samples. The frozen samples were thawed at room temperature and mixed until a uniform consistency was obtained. The homogenised human faeces (HF) sample was dried at 45 ± 5 °C in a GENLAB Hot Air Oven to constant weight. The limited drying temperature was applied to prevent the loss of volatile matter. Simulant faeces (SF) were prepared using the recipe outlined in Table 1 [22], while wood biomass (WB) was sourced locally. The relative percentages of carbon (C), hydrogen (H) and nitrogen (N) in the samples were determined using a thermal elemental analyser (Vario ELIII CHN) according to BS EN ISO 16948. The moisture content of the sample was determined at 105 ± 5 °C using the protocol outlined in BS EN 14774-3. The volatile matter and ash content were determined using a Carbolite muffle furnace with the heating conditions in BS EN 15148 and BS EN 14775 respectively. The oxygen (O) content was obtained by subtracting the wt.% percent of C, H, N and ash from 100% while the fixed carbon content was obtained by subtracting

Table 1
Recipe for simulant faeces [22].

Ingredients	Dry weight (g/kg)
Baker's yeast	72.8
Peanut oil	38.8
Miso paste	24.3
Propylene glycol	24.3
Cellulose powder	12.4
Psyllium husk powder	24.3
Calcium phosphate	25.0
Water[a]	778.1

[a] Water was added based on the required moisture content.